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Astronomers' Days, Porvoo, 4.6.2012

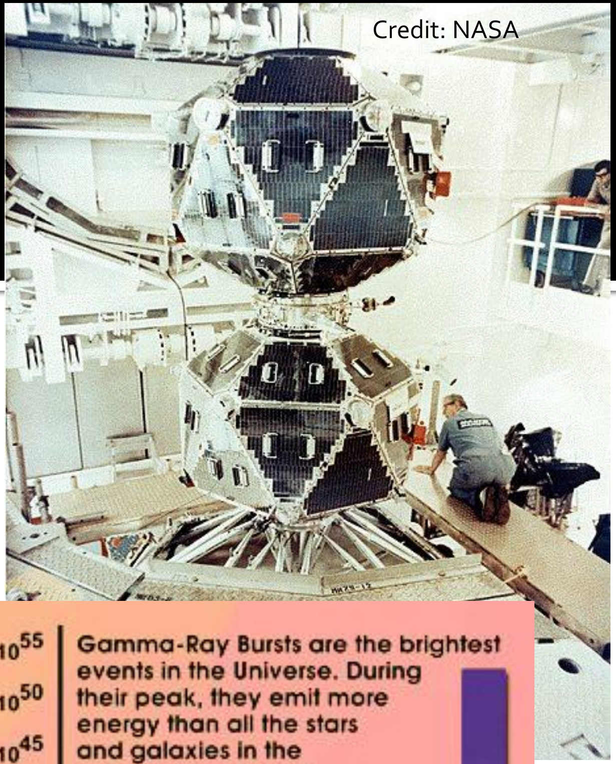
Simulations of gamma-ray burst afterglow spectra and light curves

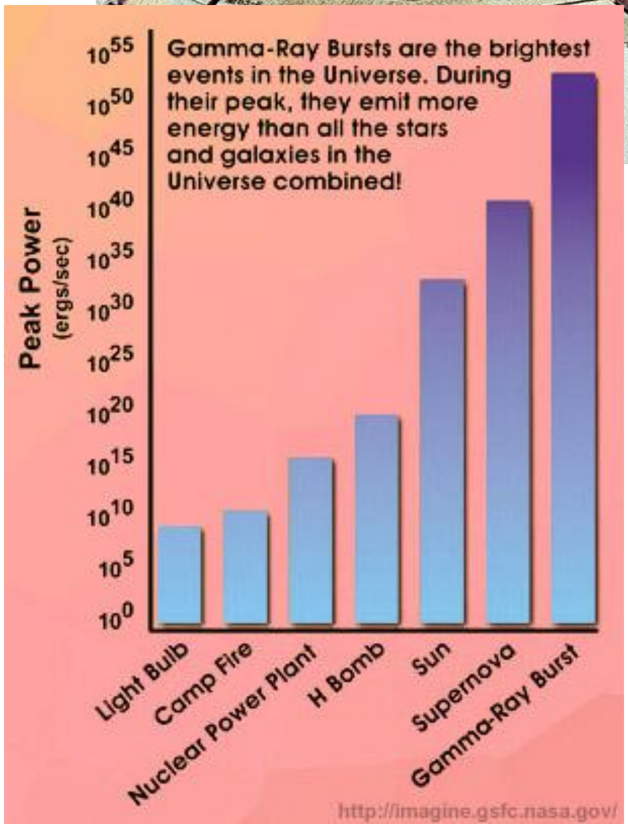
Credit: NASA/Swift/Cruz deWilde

1. Introduction

Gamma-ray bursts

- Gamma-ray bursts (GRBs) are short bursts of radiation peaking in soft gamma-rays
- Discovery by the *Vela* satellites in the 1960s
- *"Observations of Gamma-Ray Bursts of Cosmic Origin"*, Klebesadel et al. 1973, *ApJ*
- Cosmological distances up to $z \sim 9.4$
- Duration: from a few ms to thousands of seconds
- The most luminous objects observed in the Universe, releasing ~ 10^{51} erg
- Standard 'fireball' model predicts follow-up emission at lower energies: afterglow

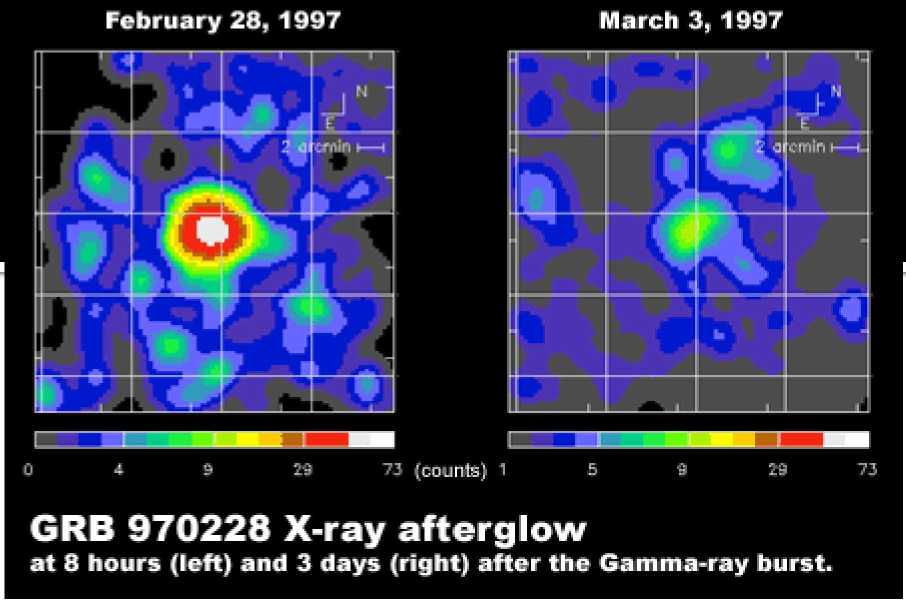




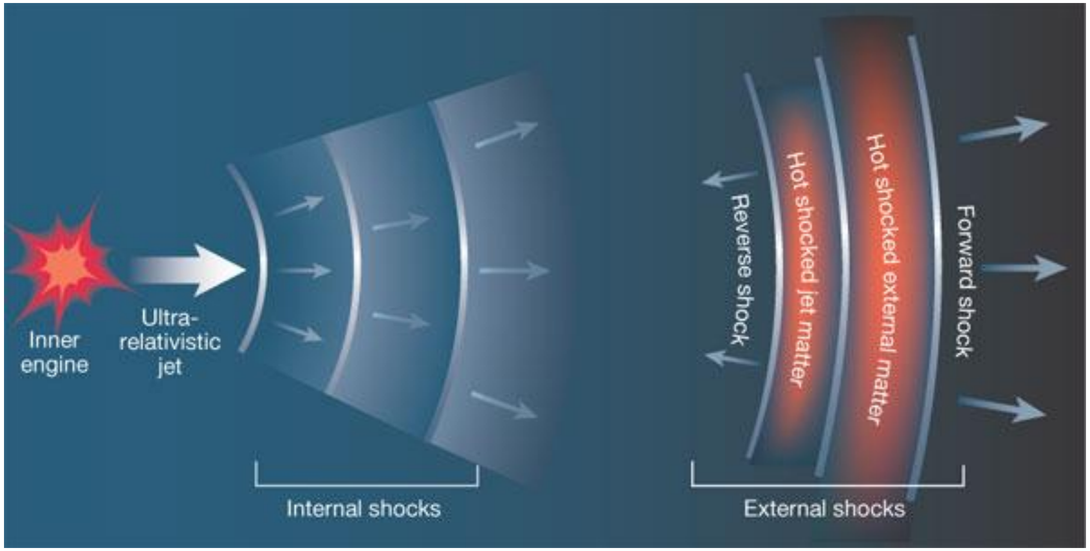
1. Introduction

Afterglows

- Discovery in 1997 by the *BeppoSAX* satellite
- Follows the prompt GRB emission in X-ray, optical and radio bands
- Observed durations from days to months
- Fireball model
  - Relativistic jet from the central engine
  - Internal shocks within the flow produce the prompt GRB?
  - External shocks (forward and reverse) produce the afterglow: accelerated electrons -> synchrotron radiation and inverse Compton scattering
  - The forward shock is typically assumed to account for the main afterglow



Credit: the Agenzia Spaziale Italiana (ASI) and the *BeppoSAX* Science Data Center (SDC)



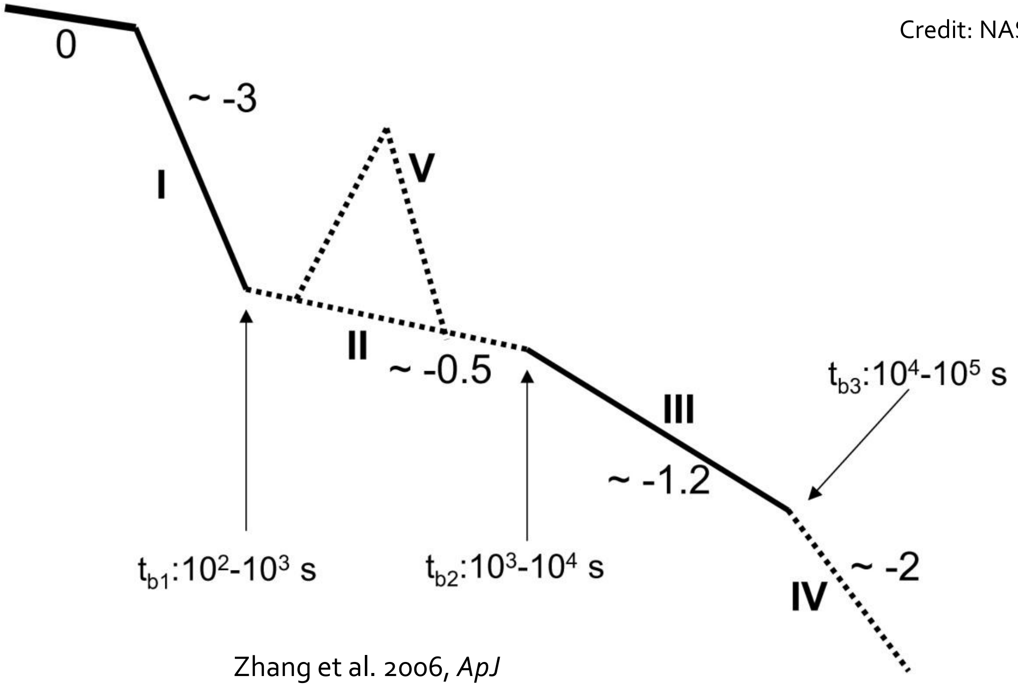
Credit: Nature Publishing Group

2. Observations

Typical X-ray light curve

Credit: NASA

- Properties of the early afterglow have been revealed by the *Swift* satellite (2004 –)
- $F \propto t^{\alpha}$
- 0: Prompt GRB
- I: Steep decay
- II: Plateau (50 – 70 %)
- III: Standard afterglow
- IV: Post jet break decay
- V: Flare (~ 30 %, internal origin)



Zhang et al. 2006, *ApJ*

Main parameters

- E_o, the energy of the shell of relativistic ejecta after the prompt GRB
- Γ_o, the initial Lorentz factor of the shell
- $n(R)$, the density of the external medium
  - ISM: n = constant
  - Stellar wind: $n(R) \propto R^{-2}$
- ε_e, the fraction of the shock energy given to the accelerated electrons
- ε_B, the fraction of energy going to the compressed magnetic field
- p, the power-law index of the electron distribution

$$\Gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

$$N(\gamma_e)\, d\gamma_e \propto \gamma_e^{-p}\, d\gamma_e, \gamma_{\min} \leq \gamma_e \leq \gamma_{\max}$$

$$\varepsilon_e = U_e / U_{shock}$$

$$\varepsilon_B = U_B / U_{shock}$$

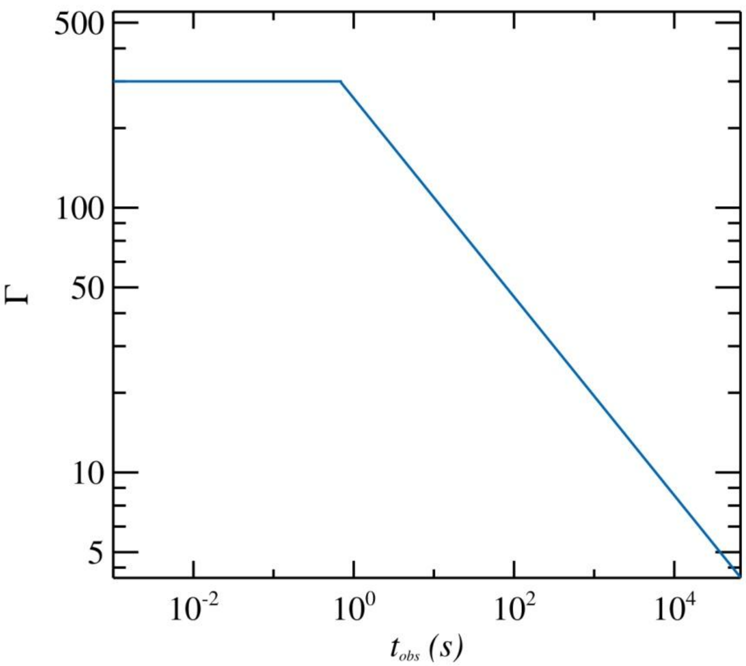
3. Standard model

Hydrodynamic evolution

- The shock initially propagates at a constant Lorentz factor Γ_o
- Deceleration (the shell has lost ~half of its initial kinetic energy) after collecting an external mass $m = M/\Gamma_o$
- After the deceleration radius, Γ and R depend on time as a power-law
- Adiabatic evolution in a constant-density ISM:

$$\Gamma \propto R^{-3/2}, R > R_{dec} = \left(\frac{3E_0}{4\pi n m_p c^2 \Gamma_0^2} \right)$$

- Synchrotron spectrum + equations for the hydrodynamic evolution -> theoretical synchrotron light curves



$$B \propto \Gamma$$

$$N(\gamma_e)\, d\gamma_e \propto \gamma_e^{-p}\, d\gamma_e, \gamma_{\min} \leq \gamma_e \leq \gamma_{\max}$$

$$\gamma_{\min} \propto \Gamma$$

+ the number of injected electrons depends on Γ

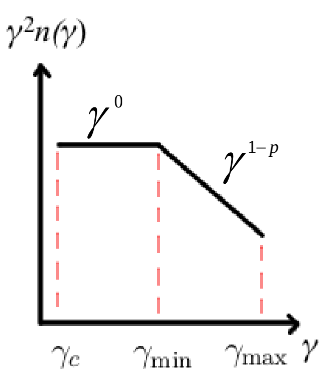
Synchrotron spectrum

- Fast cooling at early times
  - All electrons are cooling
- Slow cooling at late times
  - The bulk of the electrons do not cool
- Self-absorption affects low frequencies
- Critical Lorentz factor: $\gamma_c = \dfrac{6\pi m_e c}{\sigma_T \Gamma B^2 t}$

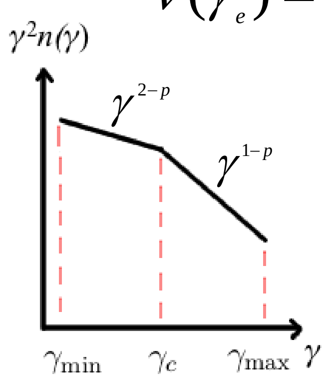
Synchrotron frequency:

$$\nu(\gamma_e) = \Gamma \gamma_e^2 \frac{eB}{2\pi m_e c}$$

Electron distribution

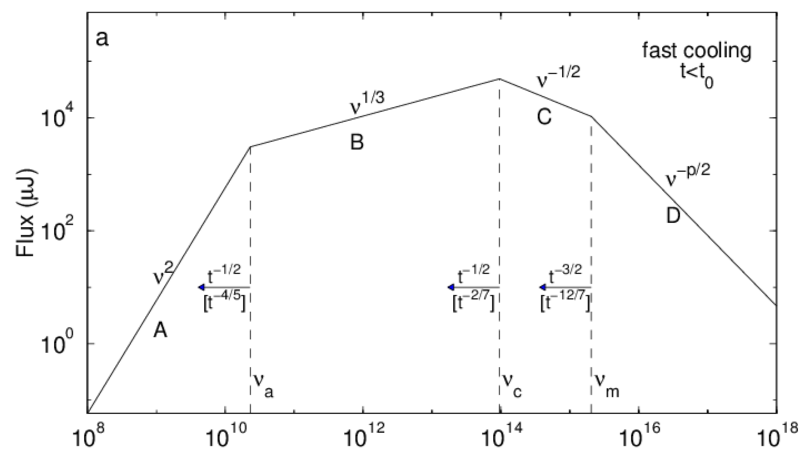


Fast cooling

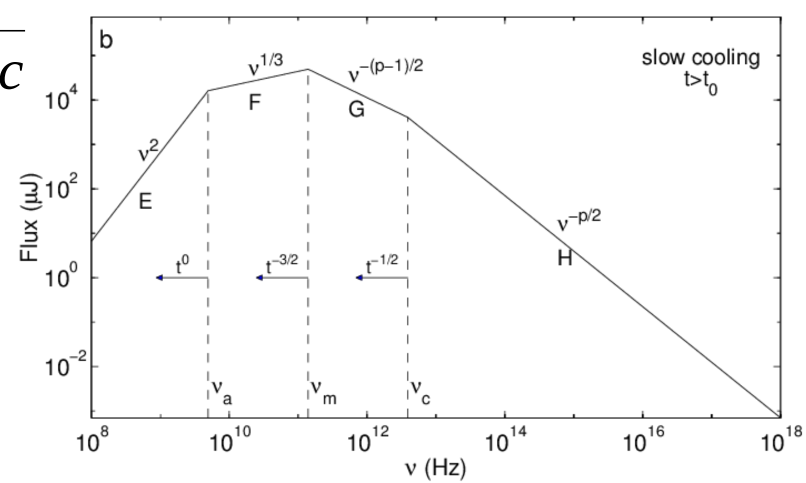


Slow cooling

Radiation spectrum



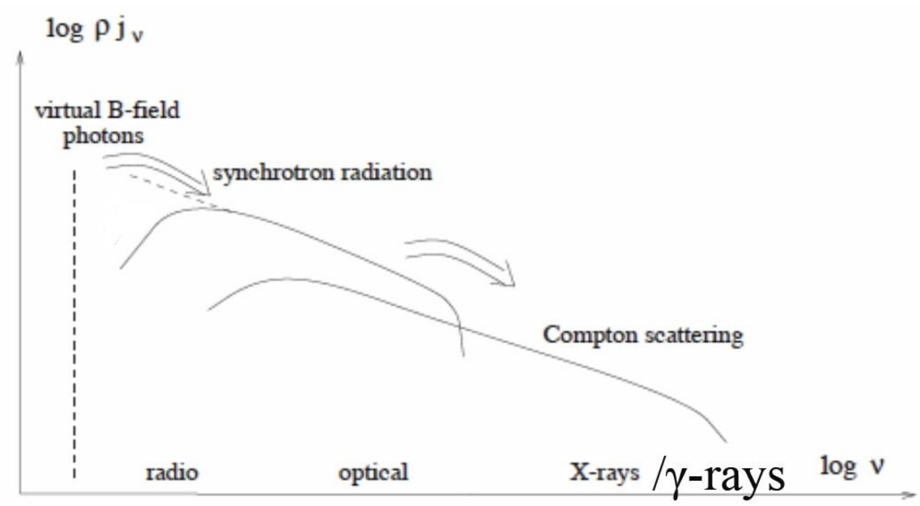
Sari, Piran and Narayan 1998, *ApJ*



Inverse Compton scattering

- A highly energetic electron gives some of its energy to a photon
- Synchrotron self-Compton (SSC): scattering of synchrotron photons by the same electrons that emitted the photons
- The importance of SSC depends on the Compton *y* parameter:

$$y = \begin{cases} \frac{\epsilon_e}{\epsilon_B}, & \frac{\epsilon_e}{\epsilon_B} \ll 1, \\ \sqrt{\frac{\epsilon_e}{\epsilon_B}}, & \frac{\epsilon_e}{\epsilon_B} \gg 1. \end{cases}$$



- SSC must be taken into account when $\varepsilon_e >> \varepsilon_B$

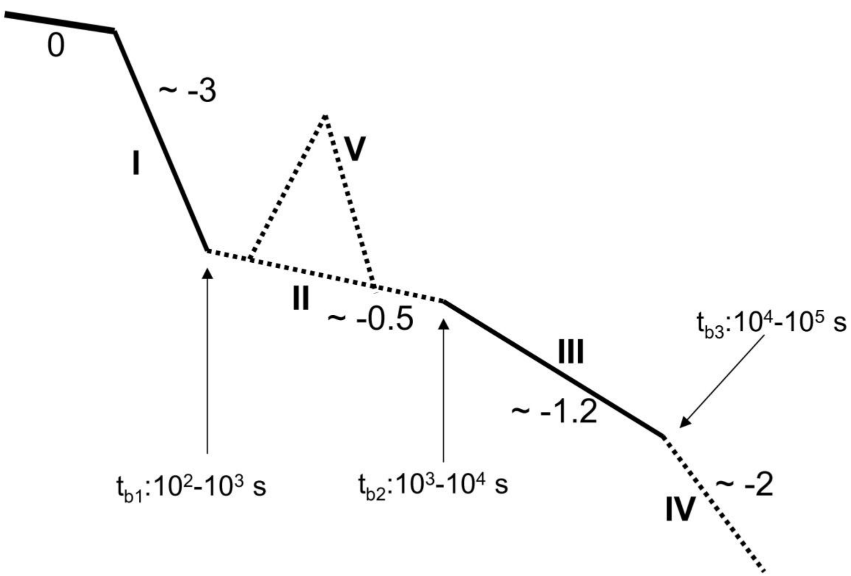
$$\varepsilon_e = U_e / U_{shock}$$

$$\varepsilon_B = U_B / U_{shock}$$

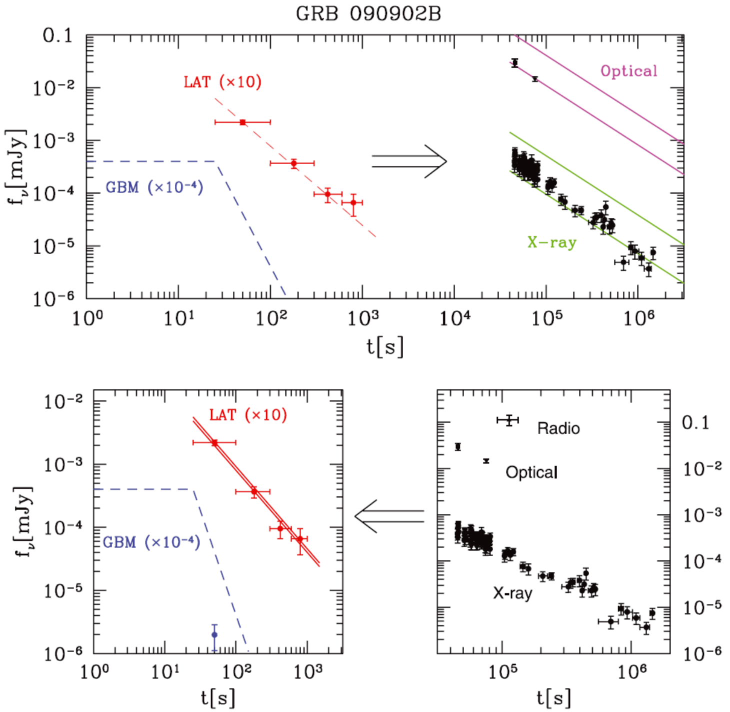
3. Standard model

Theory vs. observations

- Segments I and II in a typical X-ray light curve are not predicted by the standard model
- GeV emission
  - Delayed > 100 MeV emission with a longer duration than the lower-energy emission
  - Part of the prompt emission or the afterglow?



Zhang et al. 2006, *ApJ*



Kumar and Barniol Duran 2010, *MNRAS*

4. Numerical modeling

About the code

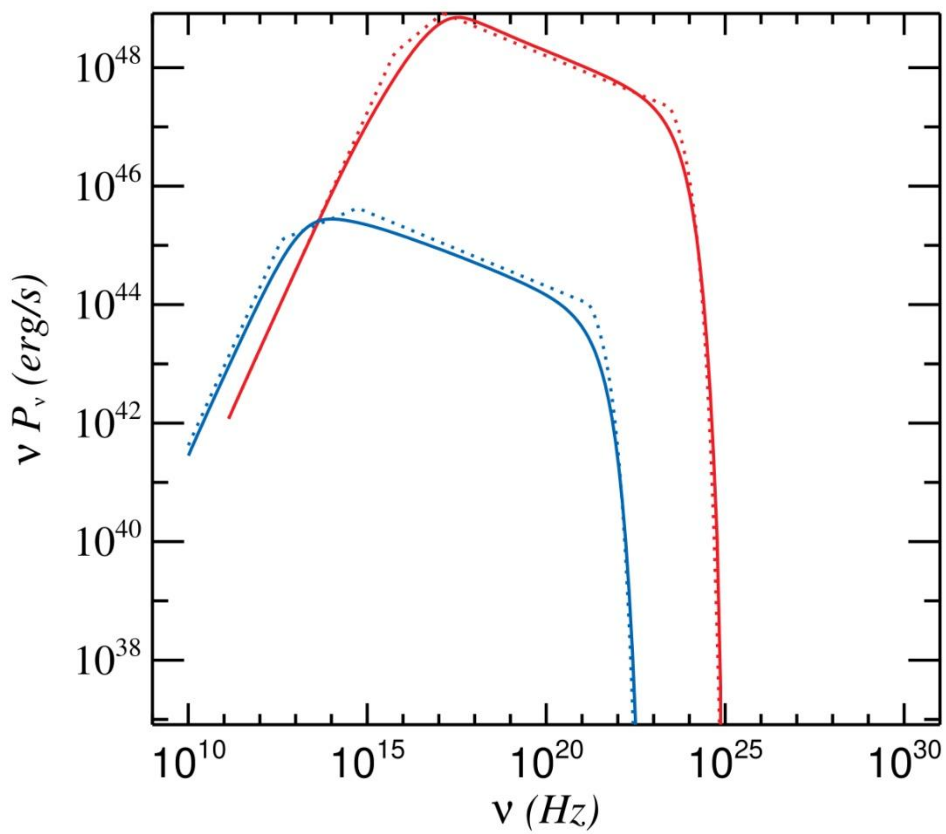
- Based on a numerical code developed to model emission from static sources (Vurm and Poutanen 2009, *ApJ* **698**, 293)
- To model afterglow emission, we solve the kinetic equations describing the evolution of electron and photon distributions simultaneously at each timestep
- Radiative processes: synchrotron radiation and self-absorption, Compton scattering, electron-positron pair production
- Adiabatic cooling + dilution of particle densities due to spreading of the emission region
- Time-evolving electron injection and magnetic field

4. Numerical modeling

Synchrotron simulations

- Simulations of synchrotron emission from the forward shock
- Parameters: $E_o = 10^{52}$ erg, $\Gamma_o = 300$, n = 1 cm^{-3}, $\varepsilon_e = 0.1$, $\varepsilon_B = 0.05$, $p = 2.5$

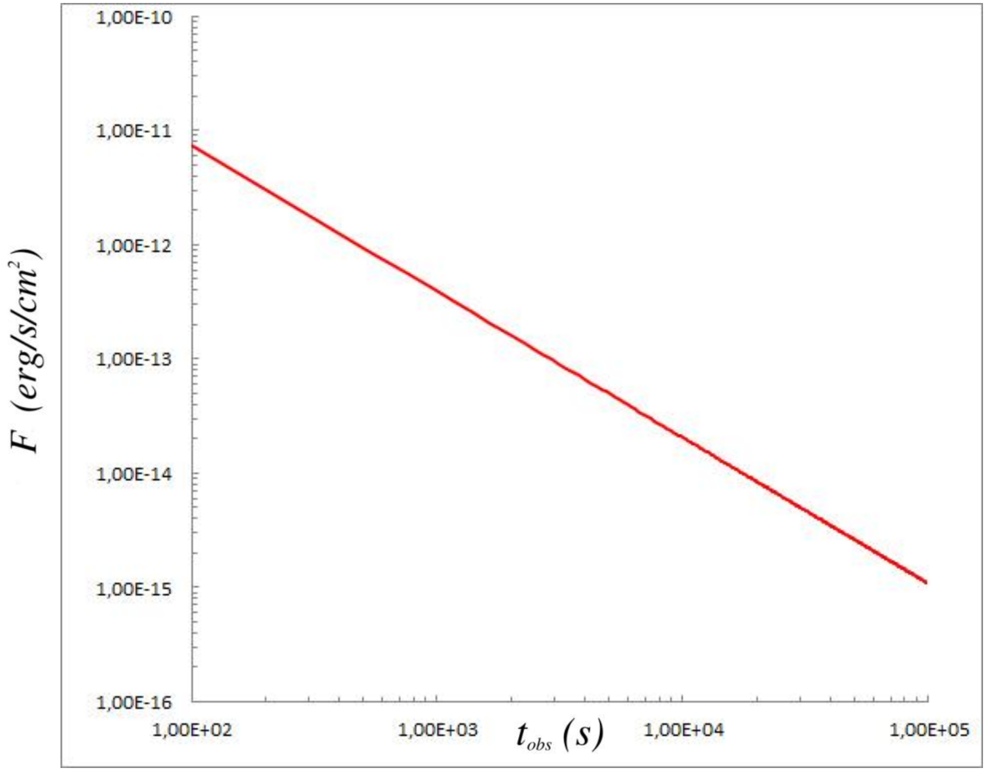
Numerical radiation spectrum (solid line) vs. the standard solution (dotted line) at observer times $t = 10$ s ($R = 1.2\ R_{dec}$, upper curves) and $t = 10^4$ s ($R = 6.7\ R_{dec}$, lower curves)



4. Numerical modeling

Synchrotron simulations

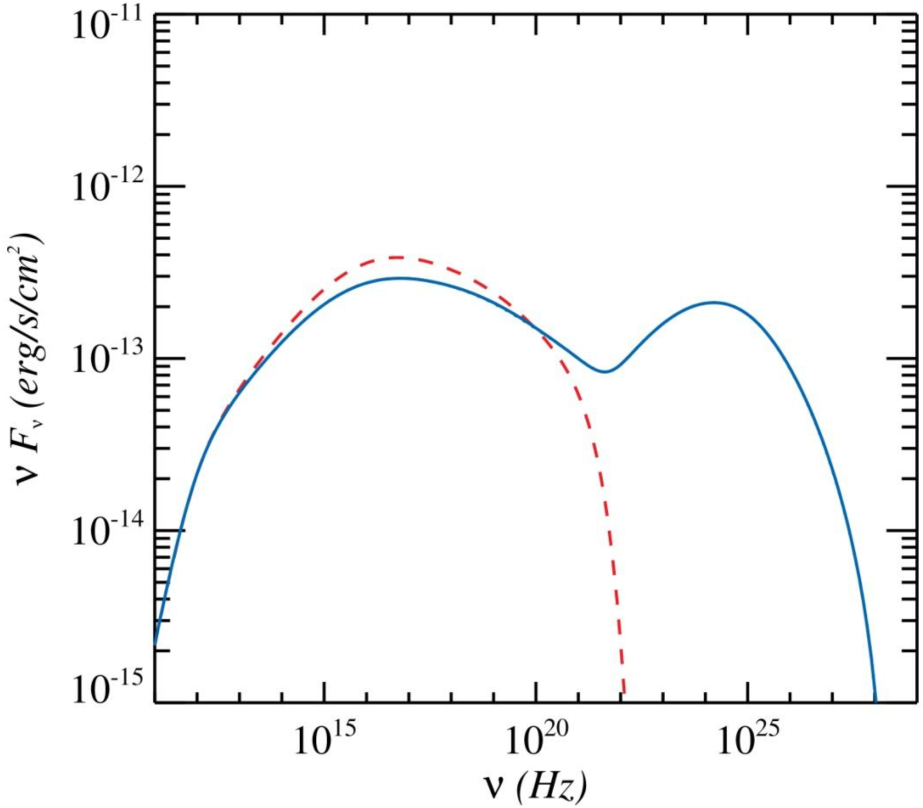
- Synchrotron light curve at a small frequency interval around E = 500 keV
- Parameters: $E_0 = 10^{53}$ erg, $\Gamma_0 = 400$, n = 1 cm^{-3}, $\varepsilon_e = 0.1$, $\varepsilon_B = 0.001$, $p = 2.3$
- Prediction of the standard model: $F \propto t^{(2-3p)/4} = t^{-1.23}$
  - The slope of the simulated light curve is consistent with the prediction



SSC simulations

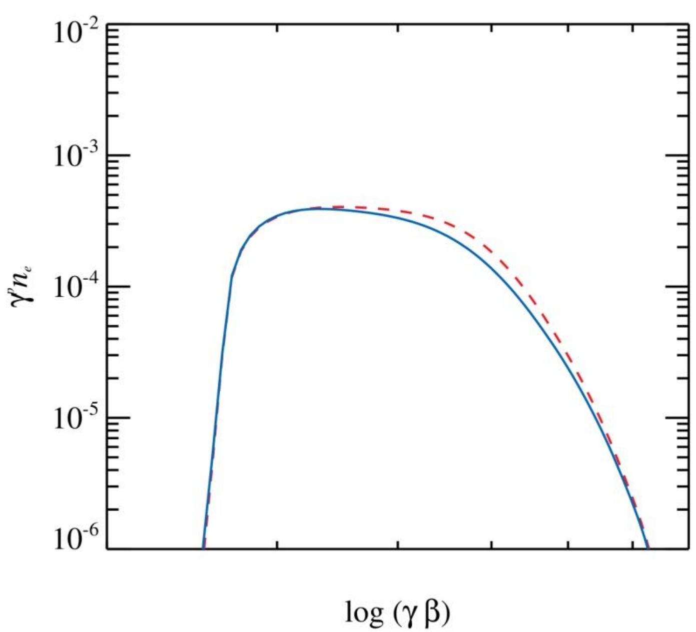
- Simulations including both synchrotron and Compton processes
- Parameters: $E_o = 10^{53}$ erg, $\Gamma_o = 400$, n = 1 cm^{-3} , $\varepsilon_e = 0.1$, $\varepsilon_B = 0.001$, $p = 2.3$
- Our results are similar to those of Petropoulou and Mastichiadis (2009, A&A)

Radiation spectrum



SSC (solid line) and synchrotron (dashed line) solutions at R = 19 R_{dec}

Electron distribution

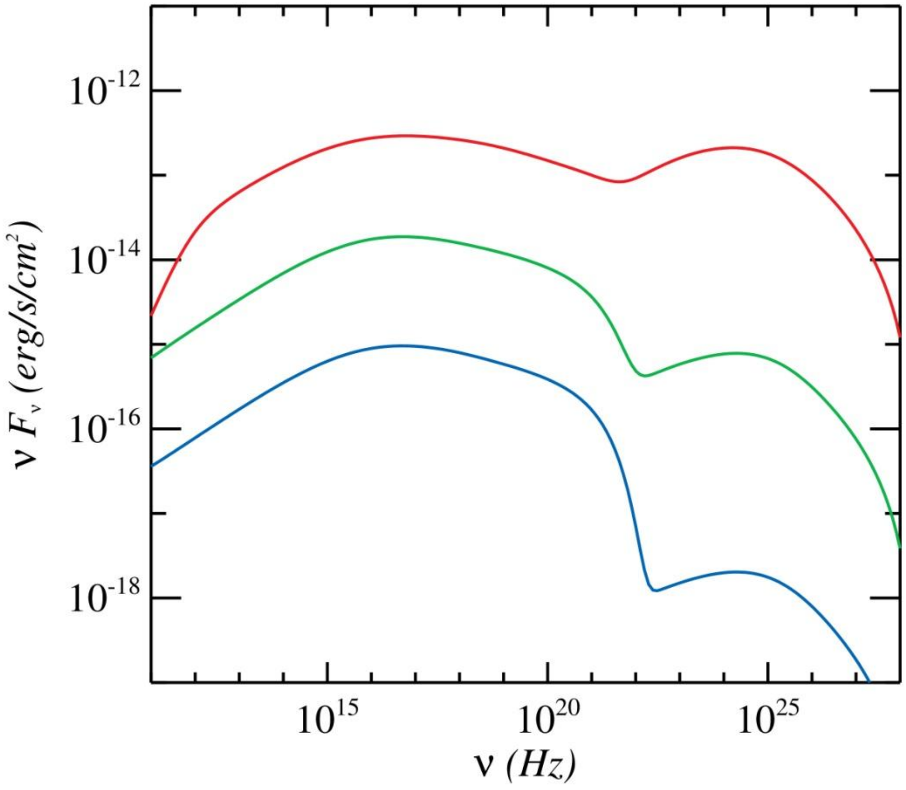


4. Numerical modeling

SSC simulations

- Importance of the *y* parameter

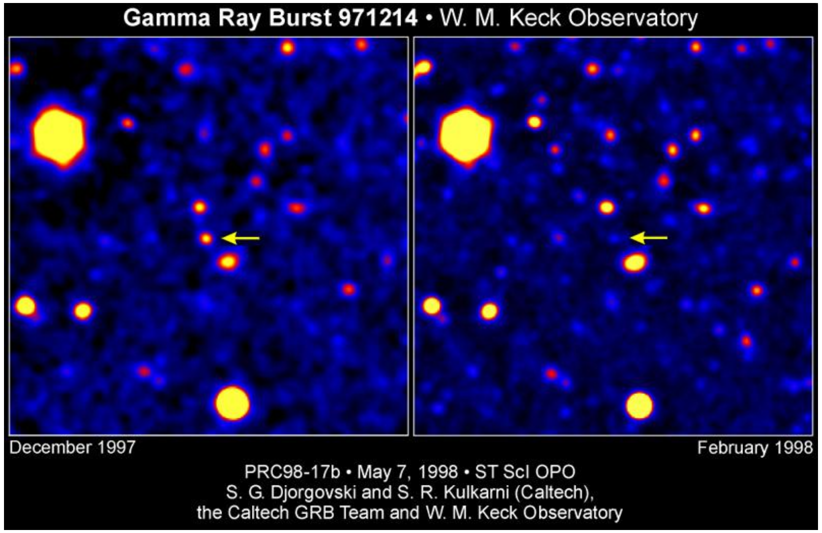
$$y = \begin{cases} \frac{\epsilon_e}{\epsilon_B}, & \frac{\epsilon_e}{\epsilon_B} \ll 1, \\ \sqrt{\frac{\epsilon_e}{\epsilon_B}}, & \frac{\epsilon_e}{\epsilon_B} \gg 1. \end{cases}$$



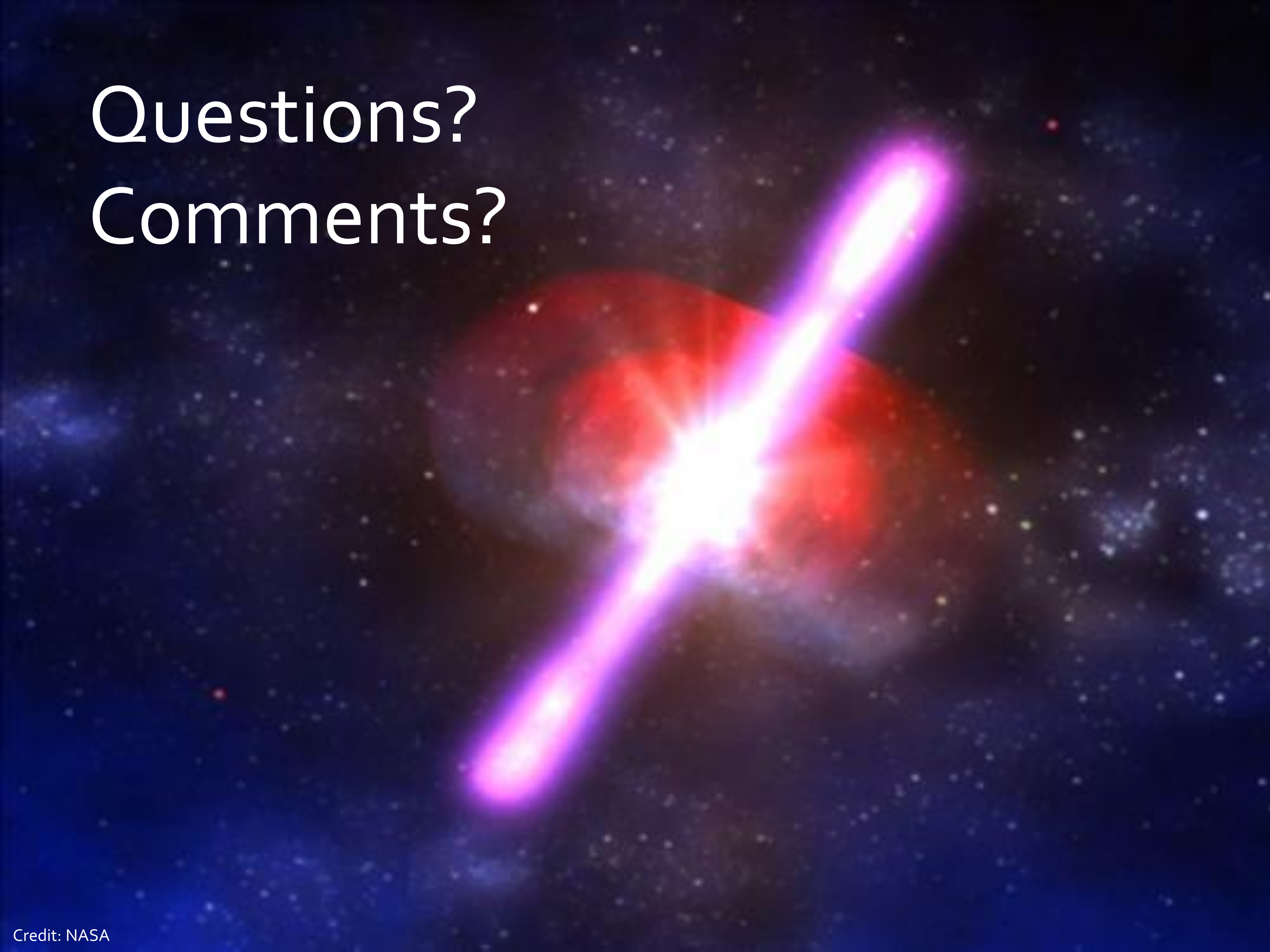
SSC spectra at R = 19 R_{dec} with ε_B = 0.001 and ε_e = 0.1 (top), ε_e = 0.01 (middle) and ε_e = 0.001 (bottom)

5. Summary

- The standard model does not explain all the observed properties of afterglows
  - The role of inverse Compton scattering?
  - Reverse shock emission?
- Our code solves the time evolution of electron and photon distributions self-consistently for any particle energies
  - The numerical synchrotron spectra are consistent with the standard solution
  - The solutions of the SSC simulations are in good agreement with results previously published in the literature
- Different models will be tested in future work



Questions?
Comments?



Credit: NASA